Precision Measurements using Atomic Systems

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

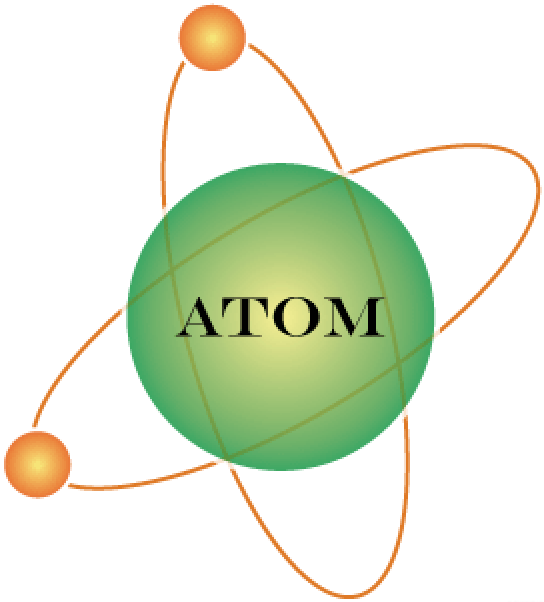
http://www.gocomics.com/nonsequitur/1994/07/21

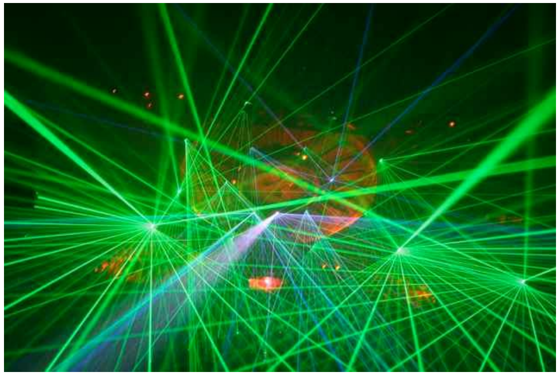
E.A.ALDEN

Leanhardt Lab

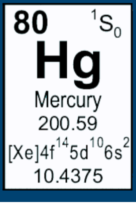
Department of Physics, University of Michigan

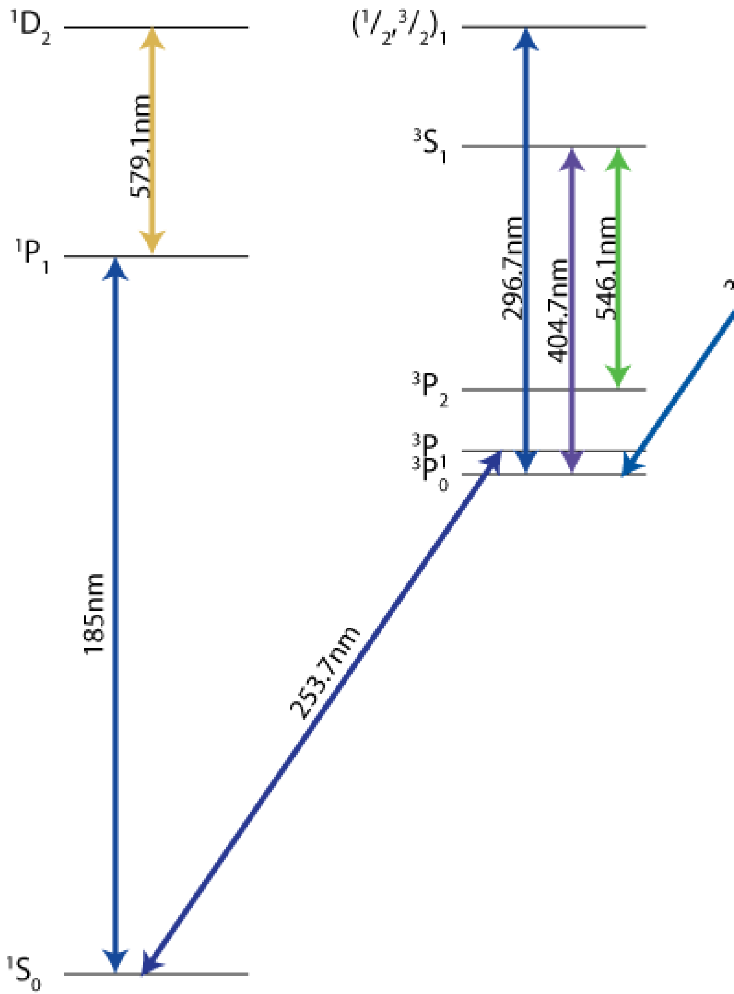
So what do you do?

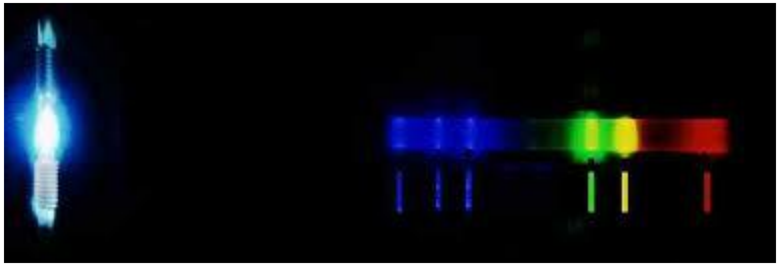




Light Interacts with Matter







What is a clock?

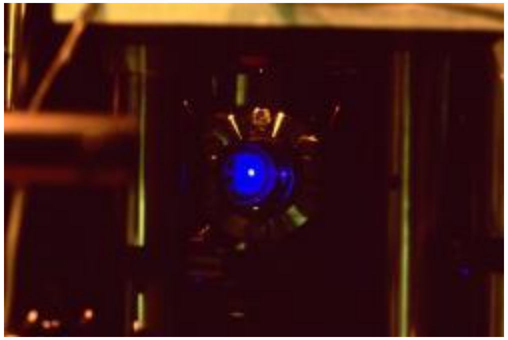
Some Examples

Mechanical Clocks

- Pendulum Clock
- Quartz Clock

Atomic clocks

- Optical clocks



Sr Optical Atomic Clock Credit: Jun Ye Group

Why Atomic Clocks?

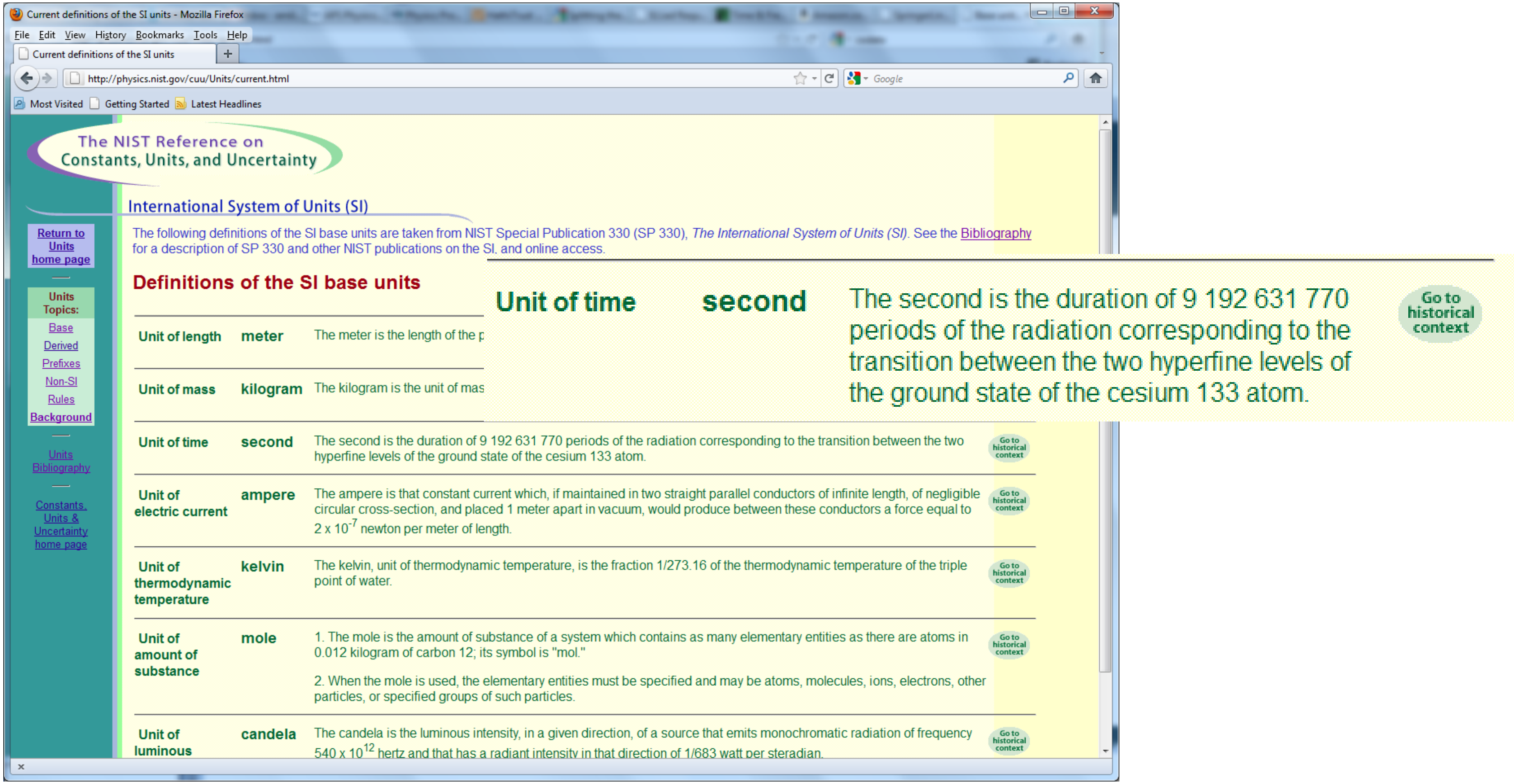
80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

EM frequencies

Atoms are stable resonators

The Internet Told Me So…

80 $^1S_0$
Hg
Mercury
200.59
[Xe]$4f^{14}5d^{10}6s^2$
10.4375


Current definitions of the SI units - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://physics.nist.gov/cuu/Units/current.html

The NIST Reference on Constants, Units, and Uncertainty

Return to Units home page
Units Topics: Base, Derived, Prefixes, Non-SI, Rules, Background
Units Bibliography
Constants, Units & Uncertainty home page

International System of Units (SI)

The following definitions of the SI base units are taken from NIST Special Publication 330 (SP 330), *The International System of Units (SI)*. See the Bibliography for a description of SP 330 and other NIST publications on the SI, and online access.

Definitions of the SI base units

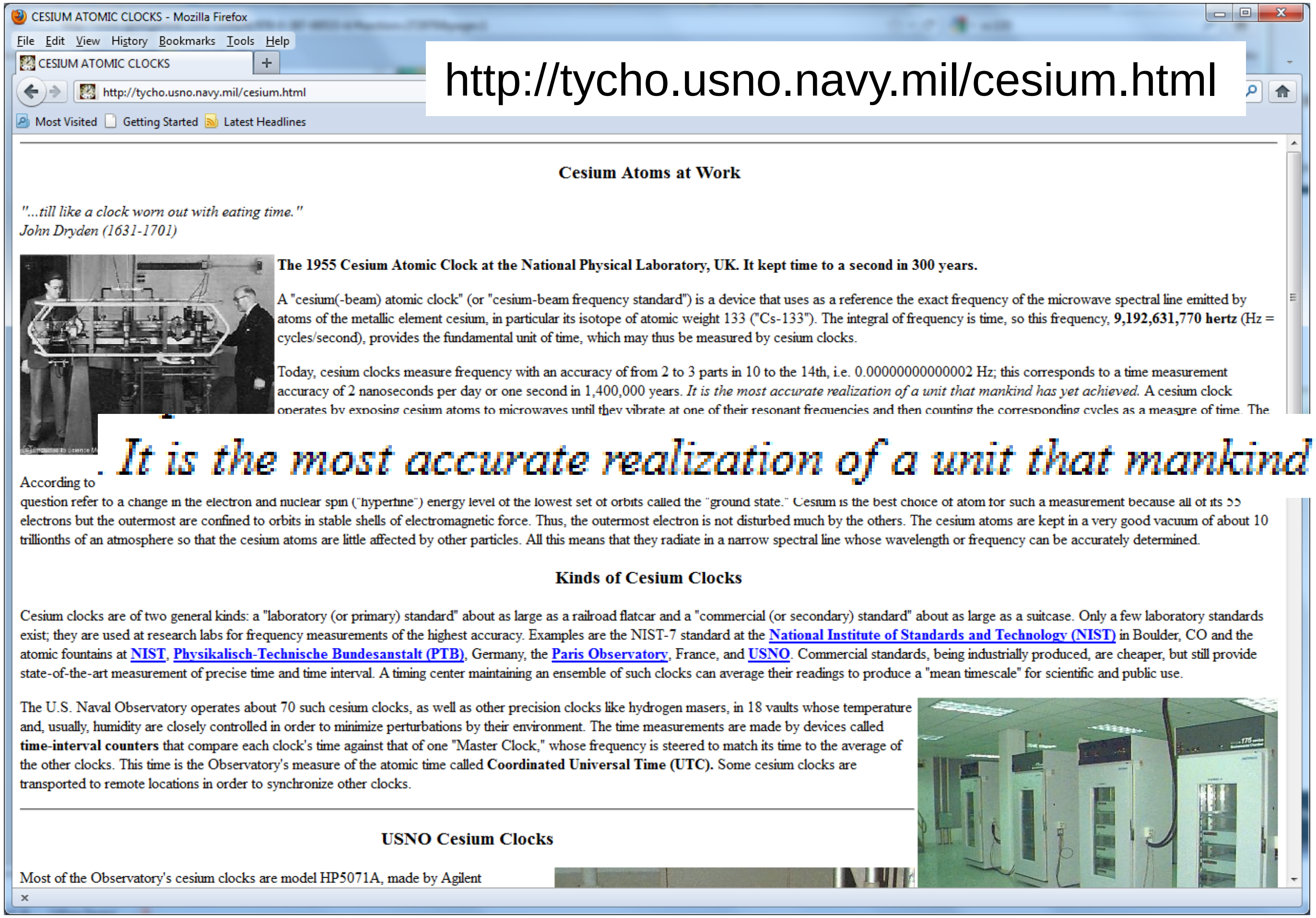
Unit of length	meter	The meter is the length of the p	
Unit of mass	kilogram	The kilogram is the unit of mas	
Unit of time	second	The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.	Go to historical context
Unit of electric current	ampere	The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per meter of length.	Go to historical context
Unit of thermodynamic temperature	kelvin	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.	Go to historical context
Unit of amount of substance	mole	1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is "mol." 2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.	Go to historical context
Unit of luminous	candela	The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.	Go to historical context

Unit of time | second | The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom. | Go to historical context

Accessed 06-2011

80 $^1S_0$
Hg
Mercury
200.59
[Xe]$4f^{14}5d^{10}6s^2$
10.4375

The Internet also said…



Cesium Atoms at Work

"...till like a clock worn out with eating time."
John Dryden (1631-1701)

The 1955 Cesium Atomic Clock at the National Physical Laboratory, UK. It kept time to a second in 300 years.

A "cesium(-beam) atomic clock" (or "cesium-beam frequency standard") is a device that uses as a reference the exact frequency of the microwave spectral line emitted by atoms of the metallic element cesium, in particular its isotope of atomic weight 133 ("Cs-133"). The integral of frequency is time, so this frequency, **9,192,631,770 hertz** (Hz = cycles/second), provides the fundamental unit of time, which may thus be measured by cesium clocks.

Today, cesium clocks measure frequency with an accuracy of from 2 to 3 parts in 10 to the 14th, i.e. 0.00000000000002 Hz; this corresponds to a time measurement accuracy of 2 nanoseconds per day or one second in 1,400,000 years. *It is the most accurate realization of a unit that mankind has yet achieved.* A cesium clock operates by exposing cesium atoms to microwaves until they vibrate at one of their resonant frequencies and then counting the corresponding cycles as a measure of time. The

According to ... question refer to a change in the electron and nuclear spin ("hyperfine") energy level of the lowest set of orbits called the "ground state." Cesium is the best choice of atom for such a measurement because all of its 55 electrons but the outermost are confined to orbits in stable shells of electromagnetic force. Thus, the outermost electron is not disturbed much by the others. The cesium atoms are kept in a very good vacuum of about 10 trillionths of an atmosphere so that the cesium atoms are little affected by other particles. All this means that they radiate in a narrow spectral line whose wavelength or frequency can be accurately determined.

Kinds of Cesium Clocks

Cesium clocks are of two general kinds: a "laboratory (or primary) standard" about as large as a railroad flatcar and a "commercial (or secondary) standard" about as large as a suitcase. Only a few laboratory standards exist; they are used at research labs for frequency measurements of the highest accuracy. Examples are the NIST-7 standard at the National Institute of Standards and Technology (NIST) in Boulder, CO and the atomic fountains at NIST, Physikalisch-Technische Bundesanstalt (PTB), Germany, the Paris Observatory, France, and USNO. Commercial standards, being industrially produced, are cheaper, but still provide state-of-the-art measurement of precise time and time interval. A timing center maintaining an ensemble of such clocks can average their readings to produce a "mean timescale" for scientific and public use.

The U.S. Naval Observatory operates about 70 such cesium clocks, as well as other precision clocks like hydrogen masers, in 18 vaults whose temperature and, usually, humidity are closely controlled in order to minimize perturbations by their environment. The time measurements are made by devices called **time-interval counters** that compare each clock's time against that of one "Master Clock," whose frequency is steered to match its time to the average of the other clocks. This time is the Observatory's measure of the atomic time called **Coordinated Universal Time (UTC).** Some cesium clocks are transported to remote locations in order to synchronize other clocks.

USNO Cesium Clocks

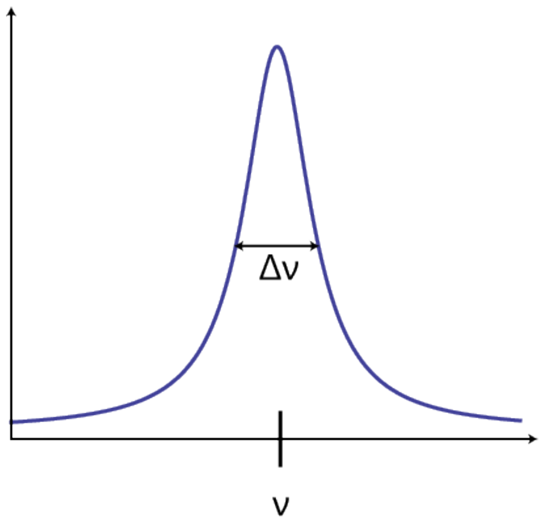
Most of the Observatory's cesium clocks are model HP5071A, made by Agilent

http://tycho.usno.navy.mil/cesium.html

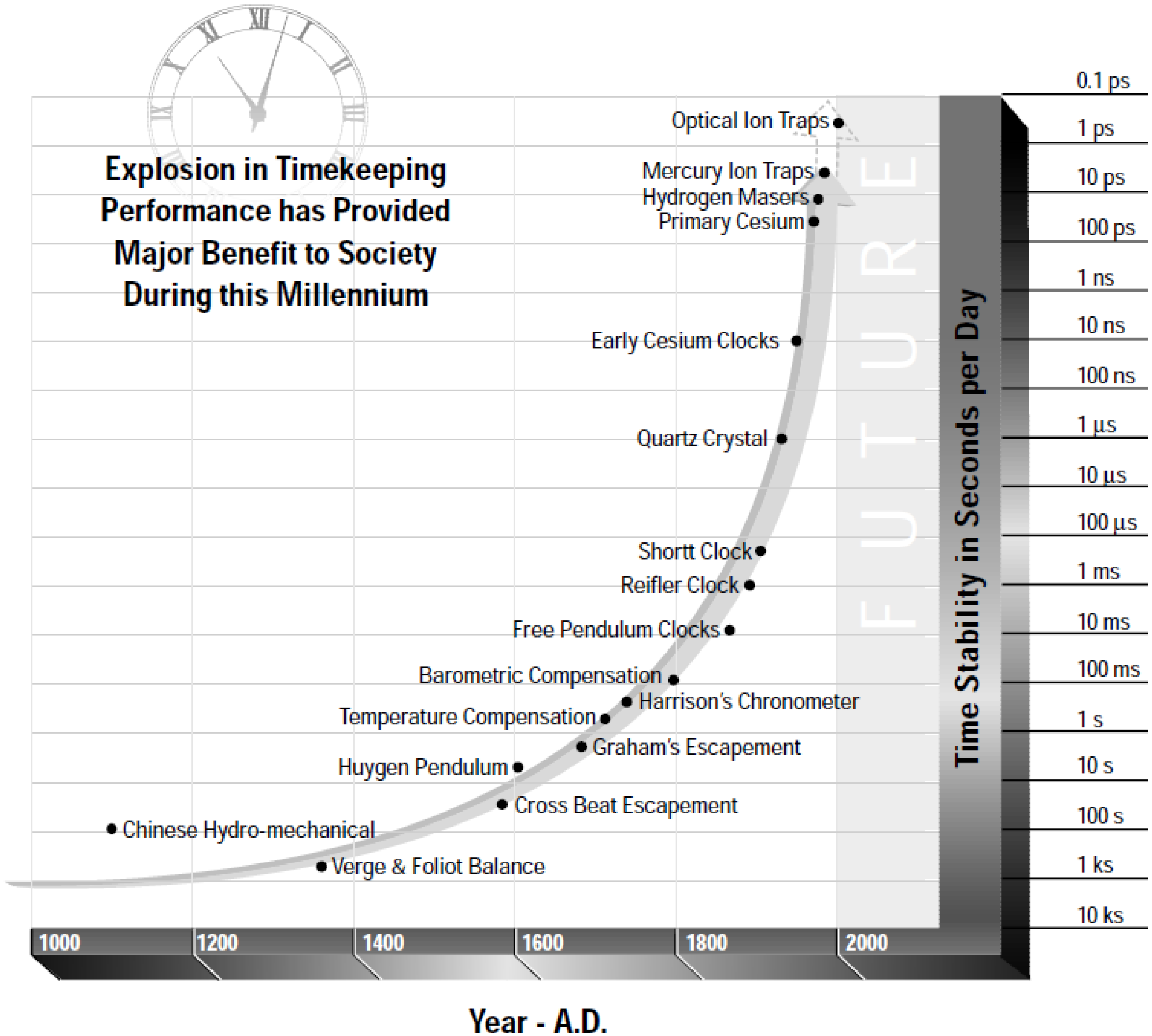
. It is the most accurate realization of a unit that mankind has yet achieved. .

How good is a clock?

$$\sigma(\tau) = \left\langle \frac{\Delta\nu}{\nu} \right\rangle_{\tau}$$



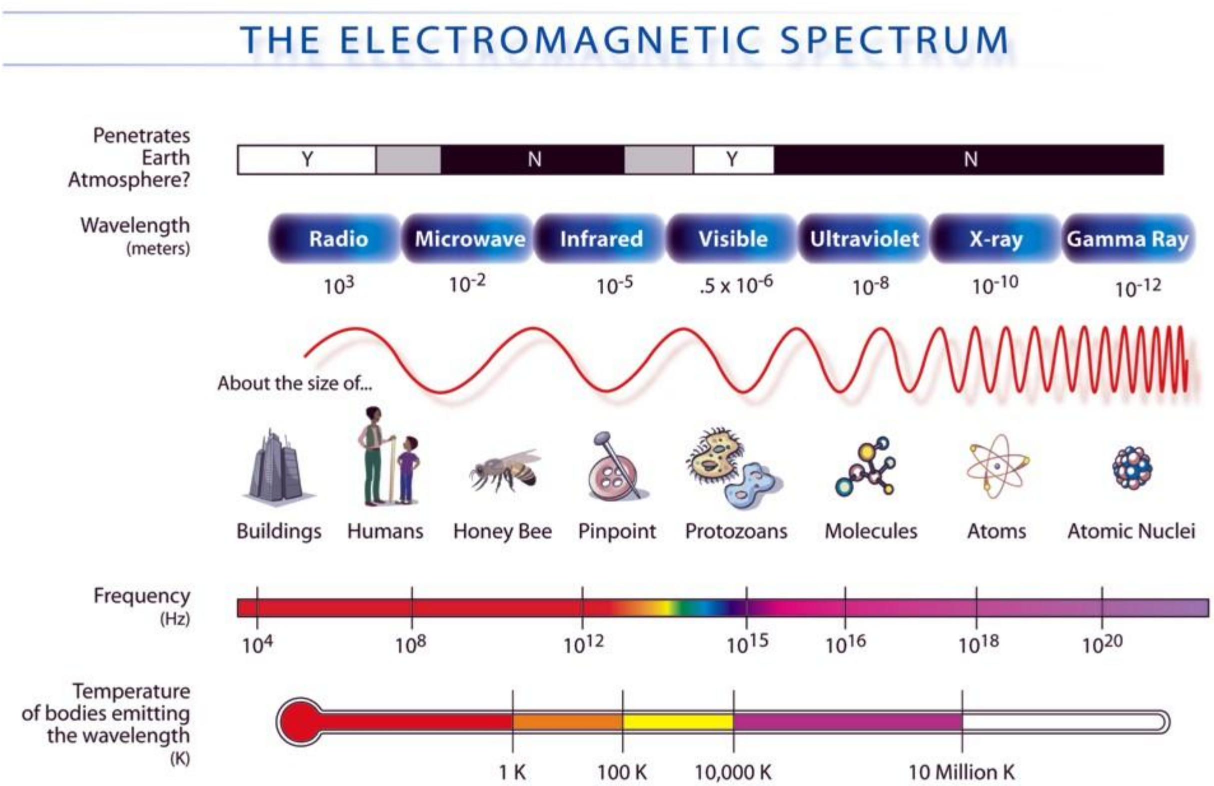
History of Clocks



D.W. Allan, N. Ashby, and C.C. Hodge, ***The Science of timekeeping***, Hewlett-Packard Application Note 1289

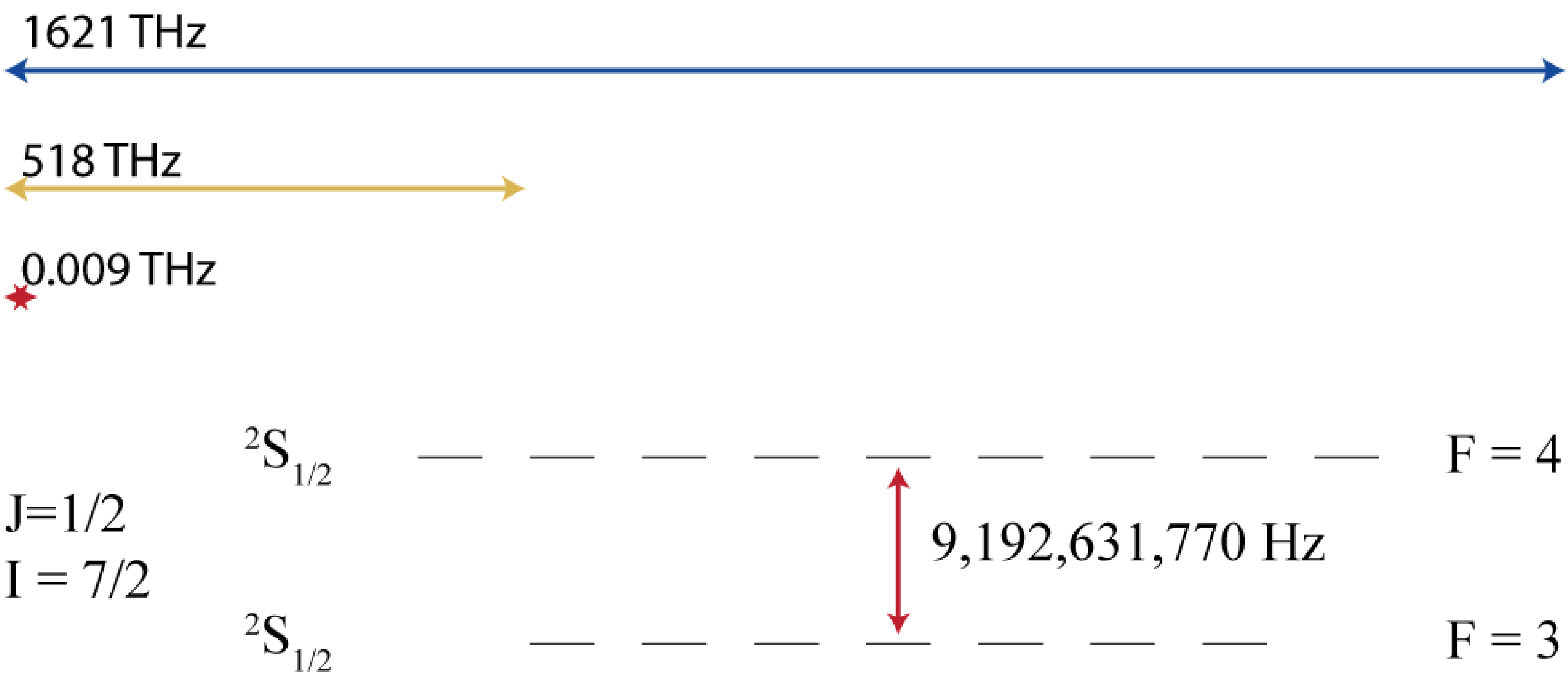
Make ν big

$$\sigma(\tau) = \left\langle \frac{\Delta \nu}{\nu} \right\rangle_\tau$$

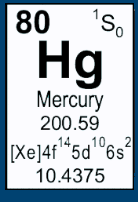


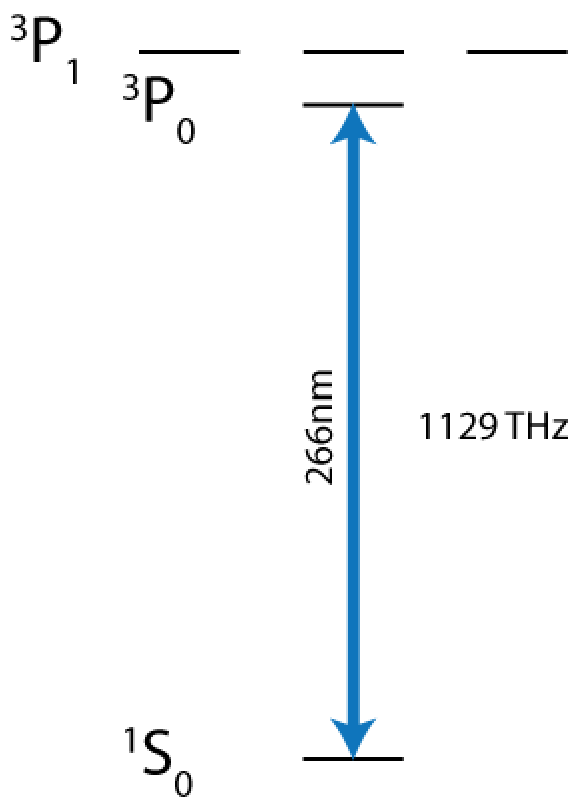
Where is ^{133}Cs?

80 $^1S_0$
Hg
Mercury
200.59
[Xe]$4f^{14}5d^{10}6s^2$
10.4375



Neutral Hg





Isotope	Spin
^{196}Hg	0
^{198}Hg	0
^{199}Hg	1/2
^{200}Hg	0
^{201}Hg	3/2
^{202}Hg	0
^{204}Hg	0

Make Δν small

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

$$\sigma(\tau) = \left\langle \frac{\Delta\nu}{\nu} \right\rangle_\tau$$

- Narrow linewidth transition
- Narrow linewidth laser
- Large number of addressed resonators
- Long coherence times
- Long measurement times
- Laser excitation geometry (transit broadening)
- So on….

TABLE I. Systematic effects that shift the clock from its ideal unperturbed frequency. Shifts and uncertainties given are in fractional frequency units ($\Delta\nu/\nu$). See text for discussion.

Effect	Shift (10^{-18})	Uncertainty (10^{-18})
Excess micromotion	−9	6
Secular motion	−16.3	5
Blackbody radiation shift	−9	3
Cooling laser Stark shift	−3.6	1.5
Quad. Zeeman shift	−1079.9	0.7
Linear Doppler shift	0	0.3
Clock laser Stark shift	0	0.2
Background-gas collisions	0	0.5
AOM freq. error	0	0.2
Total	−1117.8	8.6

13 $^2P^\circ_{1/2}$
Al
Aluminum
26.981538
$[Ne]3s^23p$
5.9858

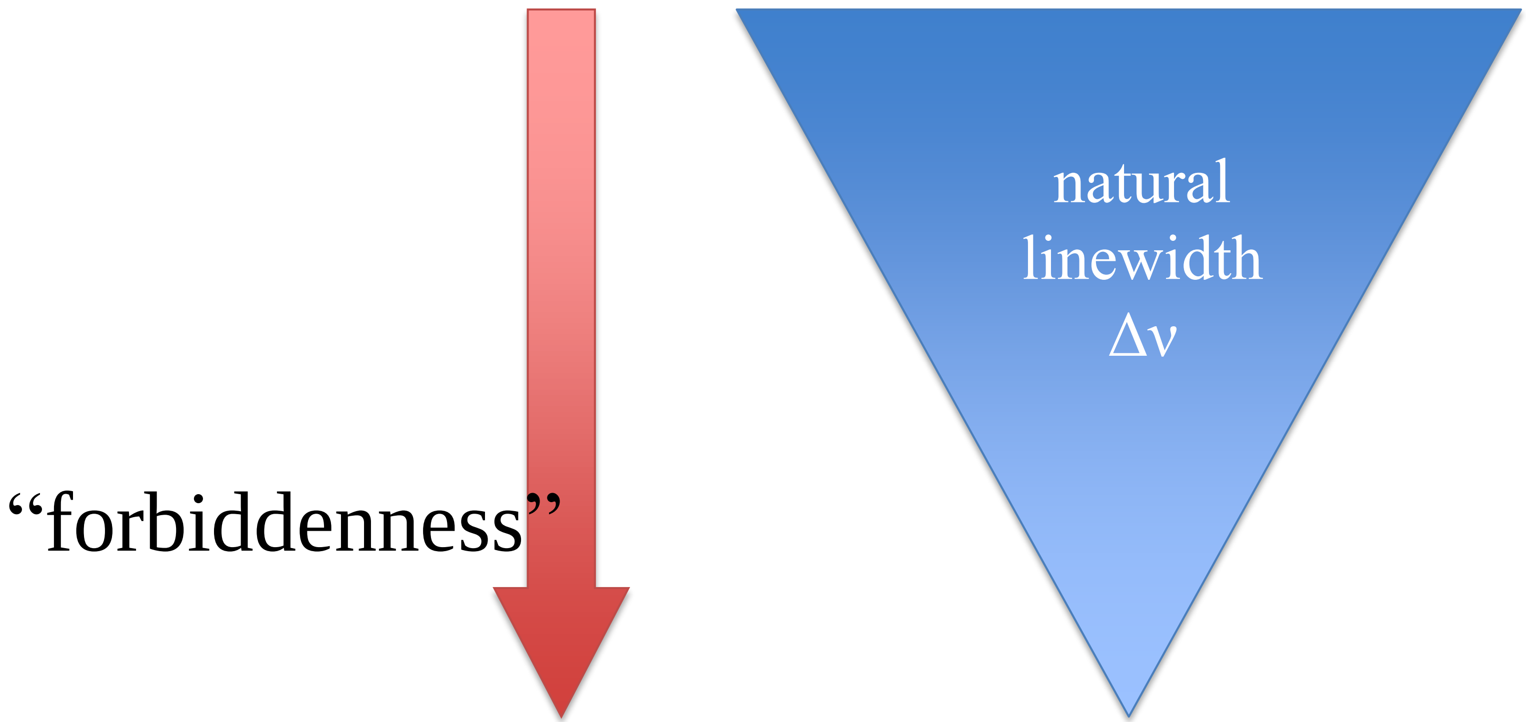
Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.95	0.03
Second-Order Zeeman	+180.91	0.025
Blackbody	-22.84	0.28
Microwave Amplitude Shift	-0.05	0.15
Spin Exchange (low density)	(-0.32)*	(0.17)*
AC Zeeman (heaters)	0.05	0.05
Cavity Pulling	0.02	0.02
Rabi Pulling	10^{-4}	10^{-4}
Ramsey Pulling	10^{-4}	10^{-4}
Majorana Transitions	0.02	0.02
Fluorescence Light Shift	10^{-5}	10^{-5}
Cavity Phase (distributed)	0.02	0.02
Second-Order Doppler	0.02	0.02
DC Stark Effect	0.02	0.02
Background Gas Collisions	10^{-3}	10^{-3}
Bloch-Siegert	10^{-4}	10^{-4}
RF Spectral purity	$3x10^{-3}$	$3x10^{-3}$
Integrator offset	0	0.01
Total Type B Standard Uncertainty		0.33

*For information purposes only. Not used in total, see section 1-B for details

55 $^2S_{1/2}$
Cs
Cesium
132.90545
[Xe]6s
3.8939

Table 1 – The list of known frequency biases for NIST-F1. This includes both the magnitude of the biases as well as the uncertainty of each individual contribution to the final uncertainty.

Choose Transition Wisely



Optical Clock Level Structure

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

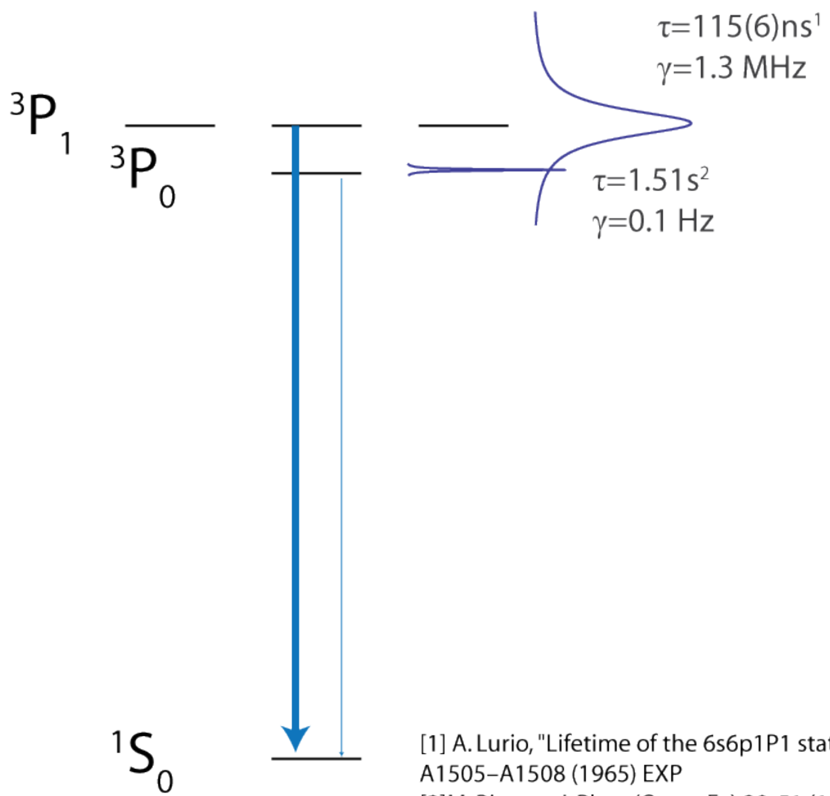
$^3P_0$

$^1S_0$

Narrow Linewidth Transition

80 $^1S_0$ **Hg** Mercury 200.59 [Xe]$4f^{14}5d^{10}6s^2$ 10.4375

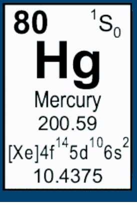
^{199}Hg I=1/2

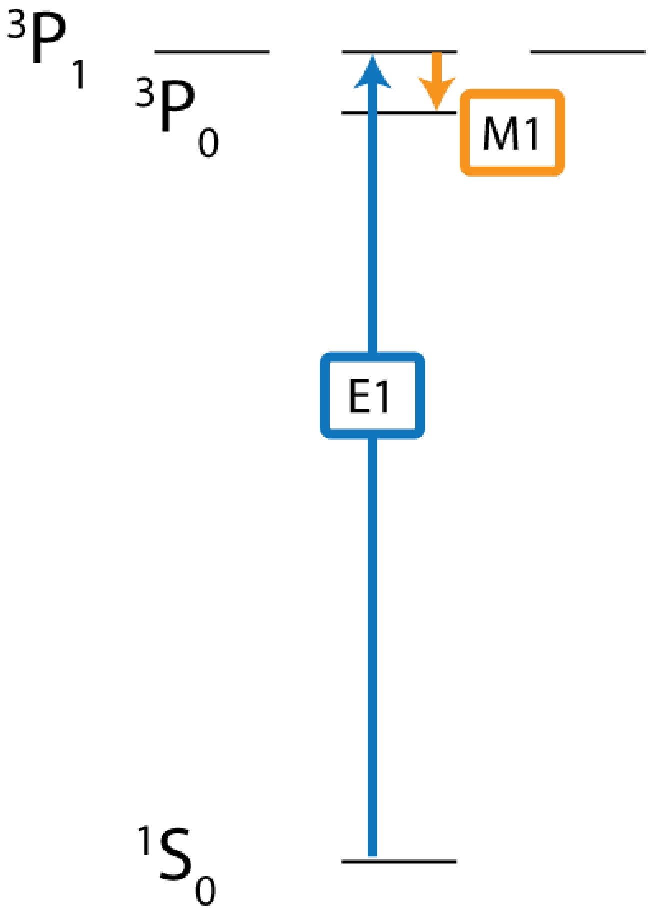


[1] A. Lurio, "Lifetime of the 6s6p1P1 state of mercury," Phys. Rev. 140, A1505–A1508 (1965) EXP

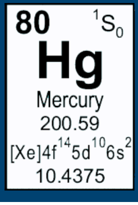
[2]M. Bigeon, J. Phys. (Orsay, Fr.) 28, 51 (1967). THEORY

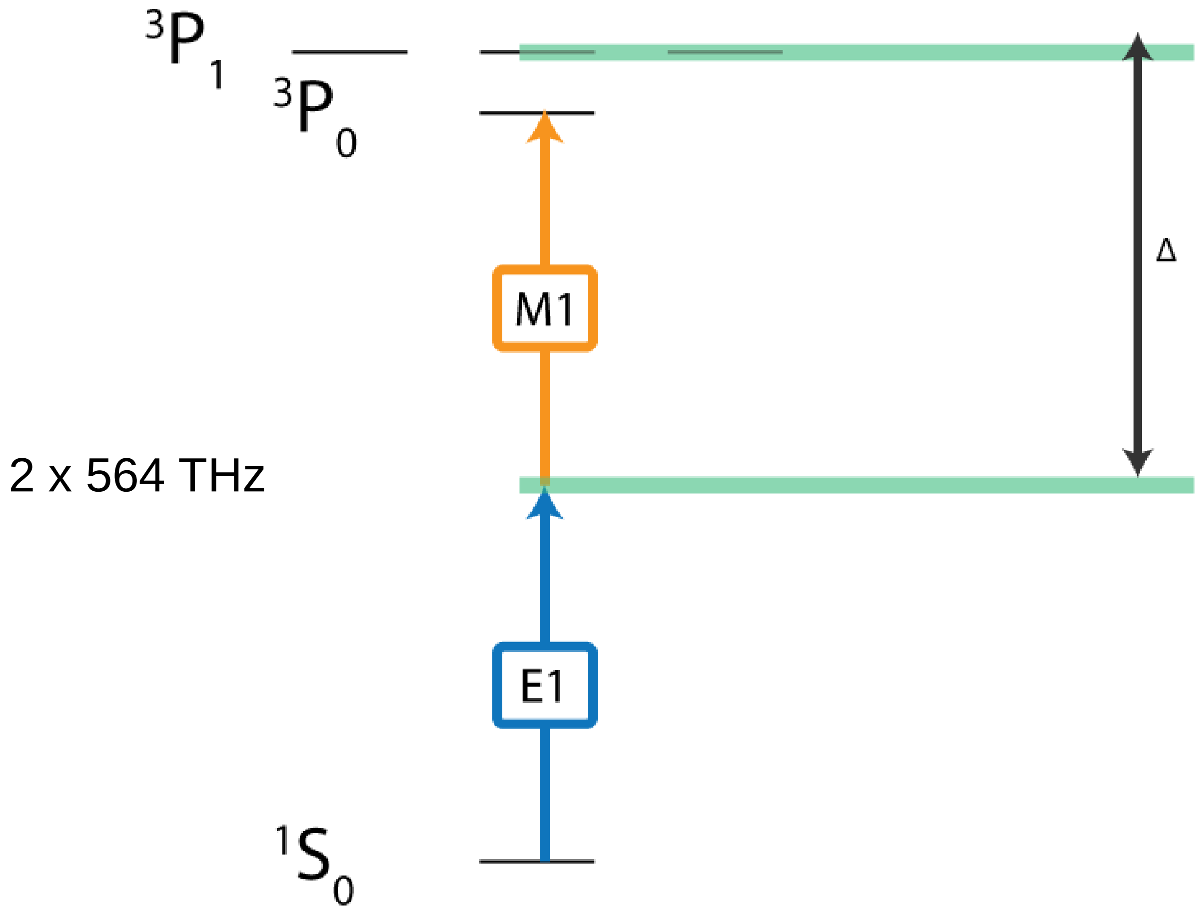
Even Narrower Transition?



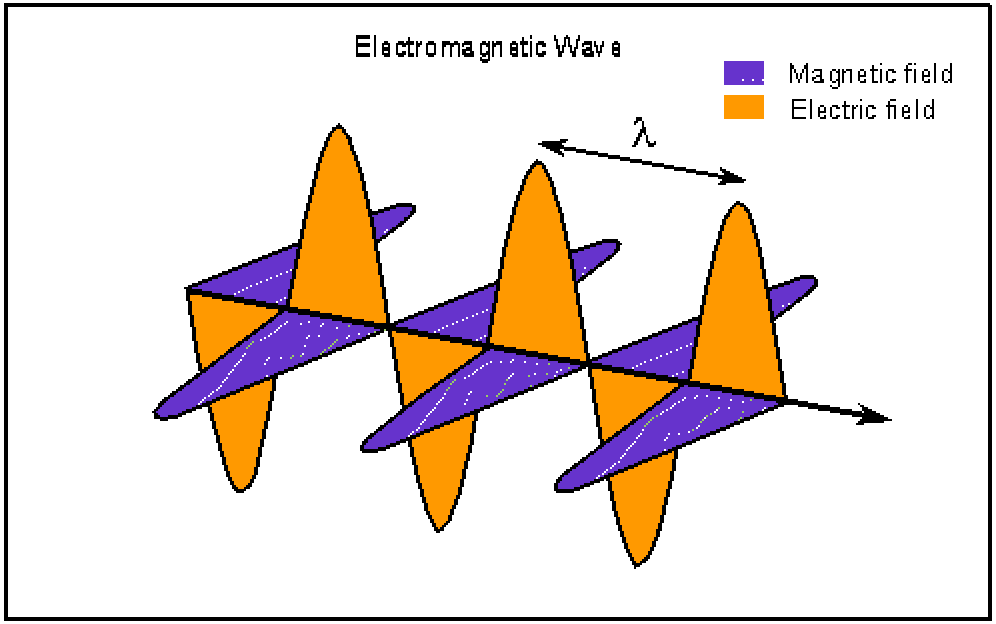


Even Narrower Transition?





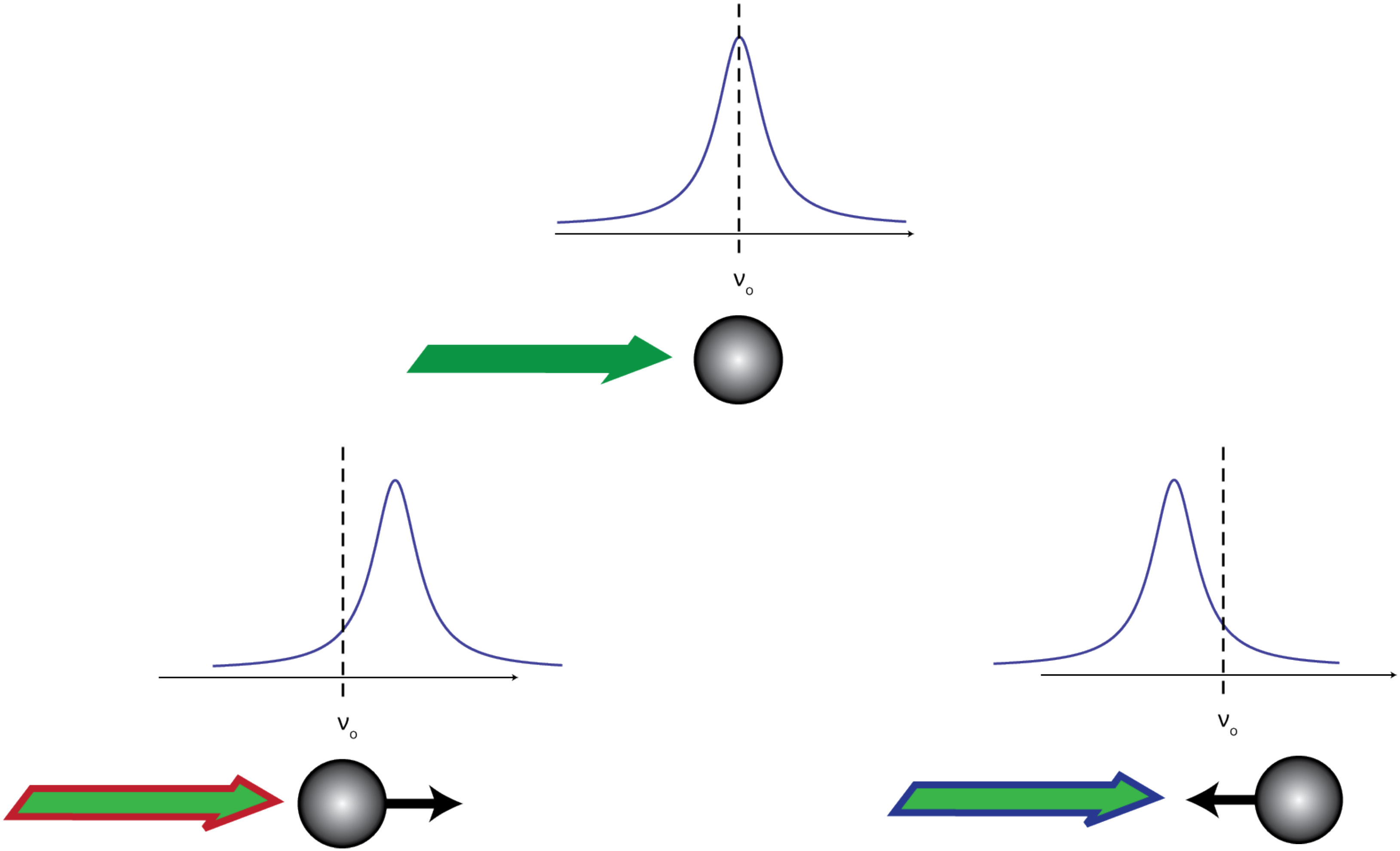
EM waves



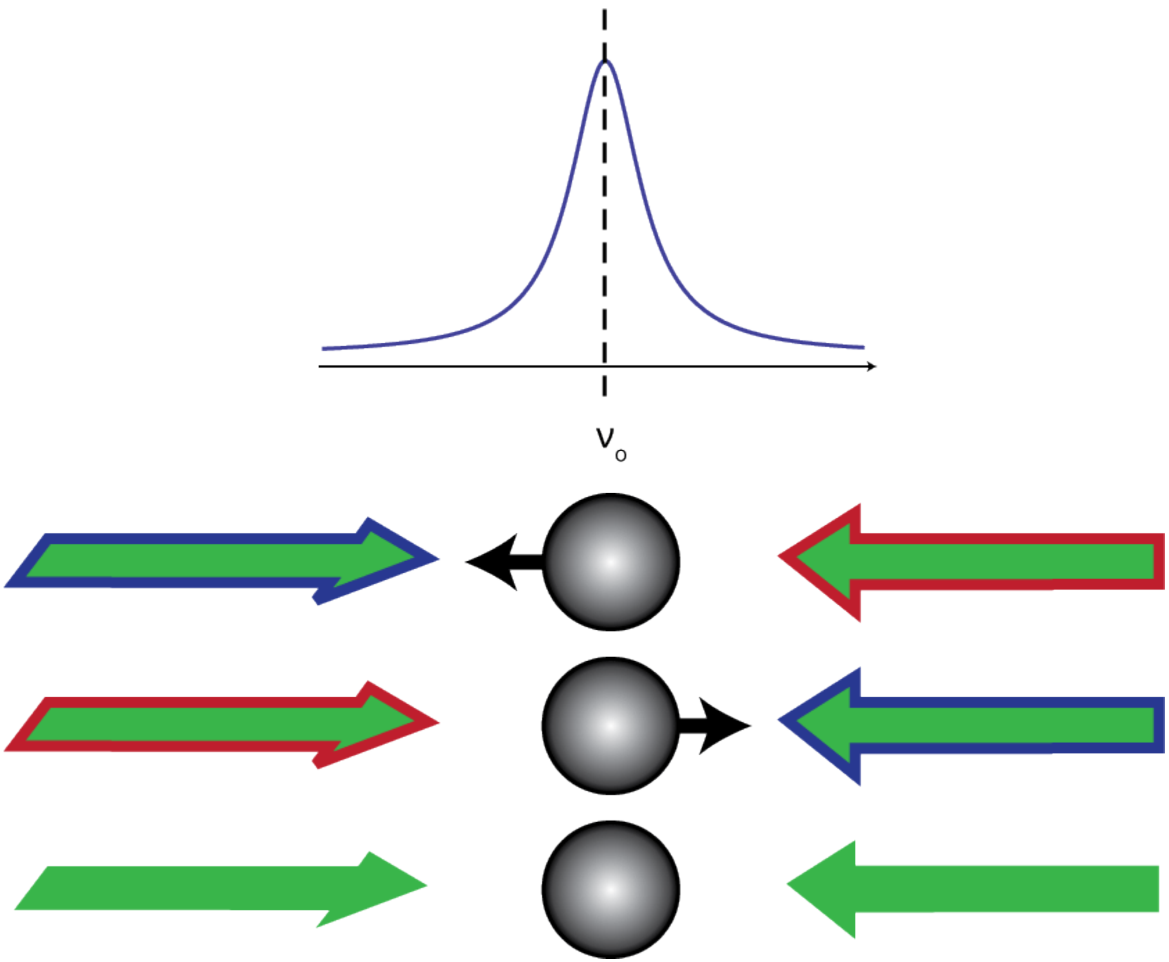
Advantages

- Linewidth preserving access to $^3P_0$ level
- Doppler-Free Spectroscopy with room temperature atoms.
- Vapor cells have high densities of atoms

Doppler Broadening



Doppler-Free Spectroscopy



Drawbacks: Transition Rates

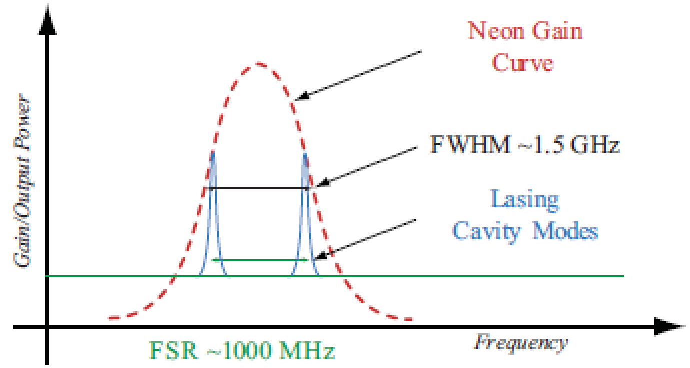
80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

$$R_{1\gamma} \propto \left\langle {}^3P_1 \middle| \mu \middle| {}^1S_0 \right\rangle_{E1}^2 I$$

$$R_{2\gamma} \propto \frac{\left\langle {}^3P_0 \middle| \mu \middle| {}^3P_1 \right\rangle_{M1}^2 \left\langle {}^3P_1 \middle| \mu \middle| {}^1S_0 \right\rangle_{E1}^2 I^2}{\Delta^2}$$

Off-the-shelf Laser

HNL008R(L) Red HeNe Laser System



Narrow Linewidth Laser

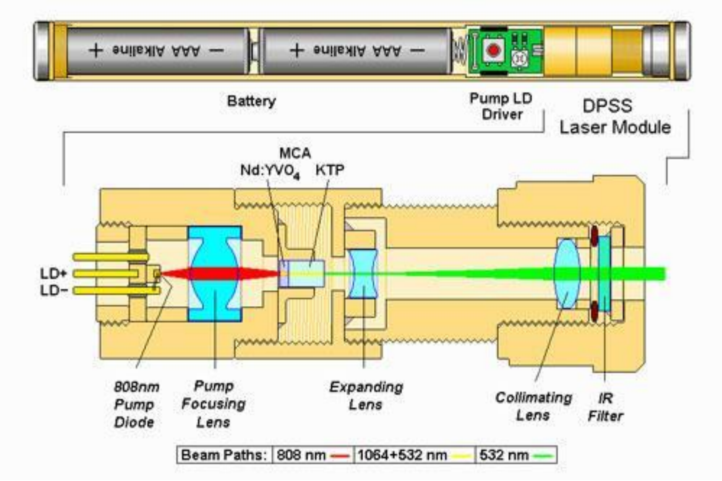
80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

- <10 kHz linewidth 1062nm @ ~10mW
- Fiber amplifier 10 mW -> 50W
- Single pass PPMgO:SLT SHG

10-25W @ 531nm

Green Laser Pointers

- 5mW w/ 1.1mm dia beam
  - ->0.58 W/cm^2
- Human eye blink time
  - – 200ms
- Damage threshold
  - –> 0.005 W/cm^2



Wikipedia 2011

- We're building a laser ->77 W/cm^2

And the point of all this…

when ↔ where

Recalculating

How do we fit into this puzzle?

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

- Explore this level structure transition
- Make clocks portable
- Map the geoid w/ 30m gravitational redshift resolution

$$\frac{\Delta\nu}{\nu}_{ESTIMATE} \approx 10^{-16}$$

The Best in the World

80 $^1S_0$ Hg
10.4375

13 $^2P^\circ_{1/2}$
Al
Aluminum
26.981538
[Ne]$3s^2 3p$
5.9858

PRL **104**, 070802 (2010) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2010

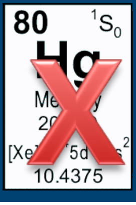
Frequency Comparison of Two High-Accuracy Al^+ Optical Clocks

C. W. Chou,* D. B. Hume, J. C. J. Koelemeij,† D. J. Wineland, and T. Rosenband
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA
(Received 23 November 2009; published 17 February 2010)

We have constructed an optical clock with a fractional frequency inaccuracy of 8.6×10^{-18}, based on

$$\frac{\Delta\nu}{\nu} = 8.6 \times 10^{-18}$$

They can see 33cm



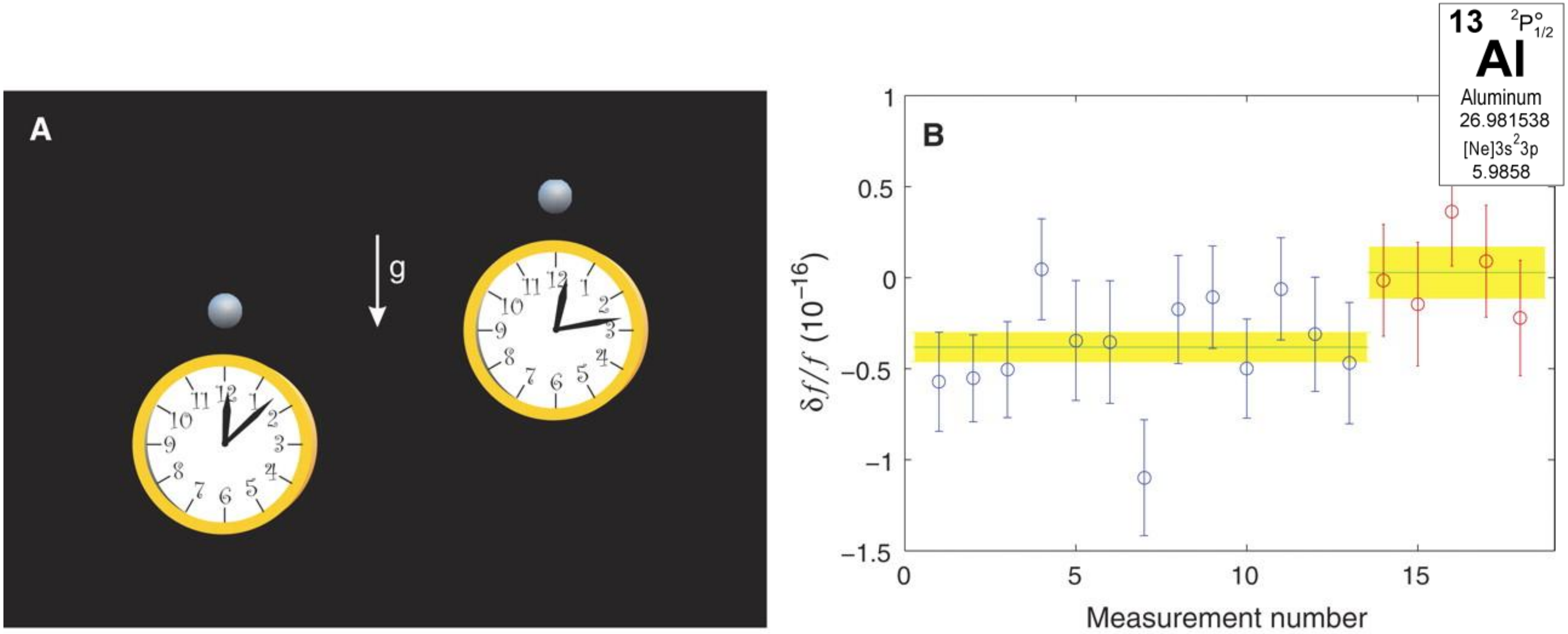


Fig. 3 Gravitational time dilation at the scale of daily life.

C W Chou et al. Science 2010;329:1630-1633

Published by AAAS

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

Leanhardt Research Group

Not Shown:
- Charlie Steiner (undergrad)

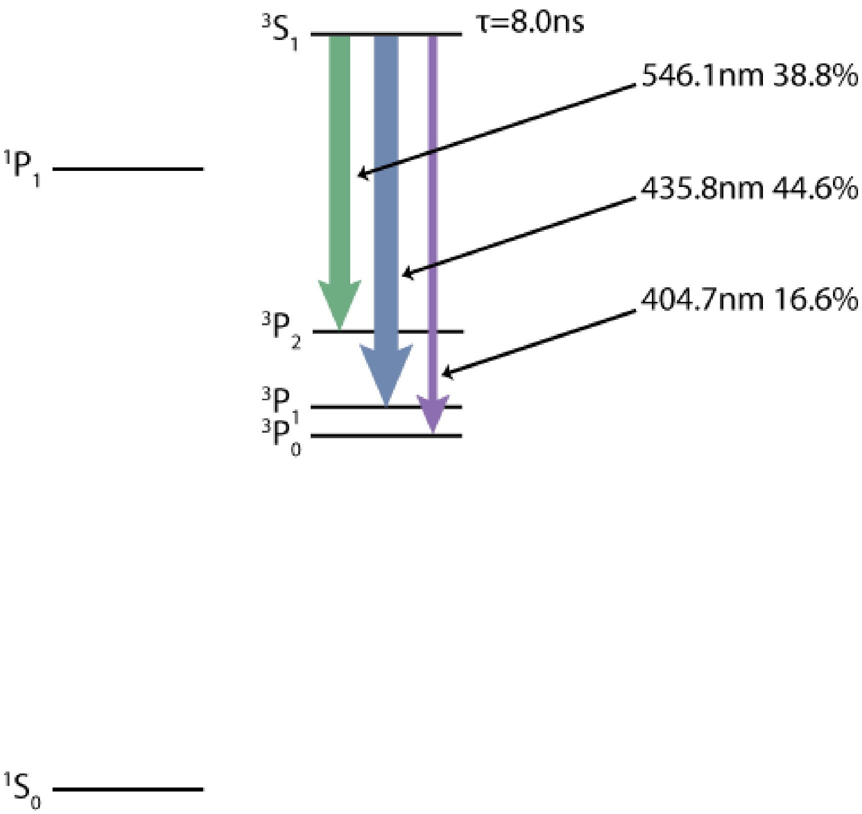
Relaxation

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

Hg Level Structure & $^3S_1$ Branching Ratios

Collision NH_3

$$Hg(^1S_0) + h\nu \rightarrow Hg(^3P_1)$$
$$Hg(^3P_1) \rightarrow Hg(^1S_0) + h\nu$$
$$Hg(^3P_1) + NH_3 \rightarrow Hg(^3P_0) + NH_3$$
$$Hg(^3P_1) + NH_3 \rightarrow Hg(^1S_0) + NH_2 + H$$
$$Hg(^3P_0) + NH_3 \rightarrow [Hg \cdot NH_3]^*$$
$$[Hg \cdot NH_3]^* \rightarrow Hg + NH_3 + h\nu'.$$



Mercury-Sensitized Luminescence of NH_3 and ND_3

By R. H. Newman, C. G. Freeman, M. J. McEwan, R. F. C. Claridge and L. F. Phillips
Chemistry Dept., University of Canterbury, Christchurch, New Zealand

Received 11th May, 1970

See Under Rug…

Mike Mosedale

- Power broadening
- Stark shifts
- Rayleigh scattering

Light Interacts with Matter

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

Atomic Clock's Figure of Merit

Allan Deviation

$$\frac{\Delta\nu}{\nu}$$

$$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu}\frac{1}{\sqrt{N\tau}}$$

Clocks

Technique	$\sigma_{<\mu>}$ @ 24 hours	Date
Pendulum	10 s	1656
Chronometer	0.4 s	1761
Quartz	10^{-4} s	1927
Cs	4.3×10^{-11} s	1952
Rb	10^{-6} s	1958
Al^+	7.4×10^{-13} s	2010